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**INVESTIGATION OF MEANS TO INCREASE REFRIGERATION
CAPACITY OF THE CHL/SATELLITE REFRIGERATION
SYSTEM OF THE FERMILAB ENERGY DOUBLER**

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FOR

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I. INTRODUCTION:

The refrigeration system of the energy doubler provides a nominal 23 kW of refrigeration at 4.6°K to the magnets of the doubler.¹ In addition to this, there is sufficient liquid helium available from the CHL to provide lead cooling. The helium refrigeration system consists of a central helium liquefier (CHL), liquid helium storage and distribution system, and twenty-four satellite refrigerators with compressors located around the ring.

The basic operation of the system is as follows:

- a) The CHL makes liquid helium from helium gas collected in a piping system around the ring and deposits this liquid in a storage tank. Rate of production is not known at this time. However, the proposed minimum rate is 4,000 l/hr, and the actual rate may be higher.
- b) The liquid helium will flow to the magnets of the doubler through a vacuum insulated transfer line in parallel with the doubler ring. This flow will be induced either by pumping with a mechanical pump or by using the pressure available at the J-T valve of the CHL. In both cases, excess liquid will be returned to the storage dewar. When using the pressure of the CHL, a subcooler will be required to turn all of the flowing helium into single phase liquid before it enters the line.
- c) Twenty-four satellite refrigerators will receive liquid helium from the distribution line upon demand, and flow rate will be controlled from sensors of each local satellite refrigerator and magnet system.

Refrigeration supplied to the magnets is provided by vaporization of liquid helium. Since there is an upper limit to the value of the heat of vaporization, flow rate is the main parameter which controls the total refrigeration made available. In a real system inefficiencies cause the refrigeration available to the magnet system to be less than the maximum available heat of vaporization. As a result of this, flow rates and size of total system increase. To increase the output from a given system, component efficiencies need to be examined and possibly improved.

II. SUMMARY AND CONCLUSIONS:

A substantial increase in refrigeration supplied by the satellite refrigerator/CHL system may be obtained by either increasing flow rate to the satellite refrigerator cold boxes or improving the efficiency of the wet engine. An increase in flow rate requires a proportional increase in CHL supplied liquid, unless the dry expander of the satellite is operated in addition to the wet expander or the capacity of the CHL is increased.

Measured performance data of the first satellite refrigerator indicate available refrigeration of 696 W at 4.5°K with a liquid helium consumption of 92 l/hr. 966 W of refrigeration at 4.6°K is projected with a flow rate of 57.5 g/sec of low pressure gas returning through the satellite cold box to the compressor. Liquid consumption is 128 l/hr.

The following conclusions may be drawn from the analysis:

- 1) Wet engine efficiency is of great importance for obtaining maximum refrigeration at lowest circulating flow rates. Table VII shows the relative importance of the efficiency on refrigeration availability.
- 2) Pressure drop of the low pressure circuit of the heat exchanger column of the satellite refrigerator should be low. Table I shows the effect.
- 3) Additional refrigeration may be obtained from the satellite refrigerator through increase of circulating flow rate at constant liquid helium supply by operating the dry expansion engine at low throughputs. The reciprocating expander lends itself admirably to provide high efficiency at low throughputs.
- 4) The liquefaction rate of the CHL may be increased by 10-20% through the addition of equipment. A minimal amount of equipment, consisting of three expanders and a small cold box operating between 80 and 18°K will supply an extra 500 l/hr of liquid helium.

III. DETERMINATION OF REFRIGERATION AT THE ENTRANCE TO THE MAGNET SYSTEM:

Refrigeration is supplied to the magnets by vaporization of liquid helium. If we assume that the maximum temperature of the returning two phase stream (while in contact with the magnets) cannot exceed 4.5°K, then highest enthalpy of the vapor returning to the refrigerator is a function of pressure as shown in Table I:

T A B L E I

<u>Pressure atm</u>	<u>Temp. °K</u>	<u>Enthalpy J/gr</u>
1.3	4.5	29.75
1.2	4.5	30.76
1.0	4.5	32.54
.9	4.5	33.28
.8	4.5	33.95

The liquid flowing to the magnets as single phase flow will be maintained at a pressure of 1.6 to 1.8 ata (8.82 to 11.76 psig). The lowest temperature of this liquid entering the magnets is 4.5°K because of intimate thermal contact with the returning two phase stream. Enthalpy of the liquid is then 11.20 J/gr. Maximum available amount of refrigeration from 1 gram of circulating fluid is then a function of pressure of two phase flow as given in Table II. A change in inlet enthalpy to the magnet will reduce the refrigeration available to the magnets as shown in Columns 3 and 4 of Table II:

T A B L E I I

<u>Pressure 2 Ø Stream ata</u>	<u>Refrigeration per Gram of Gas = f (Inlet Enthalpy) J/gr</u>		
	H = 11.2	13.0	14.5
1.3	18.55	16.75	15.25
1.2	19.56	17.76	16.26
1.0	21.34	19.54	18.04
.9	22.08	20.28	18.74
.8	22.75	20.95	19.45

It should be noted that the numbers of Table II are based on returning vapor from the two phase stream of the magnet to the satellite refrigerator at 4.5°K. Columns 3 and 4, therefore, represent inefficiency of the wet engine.

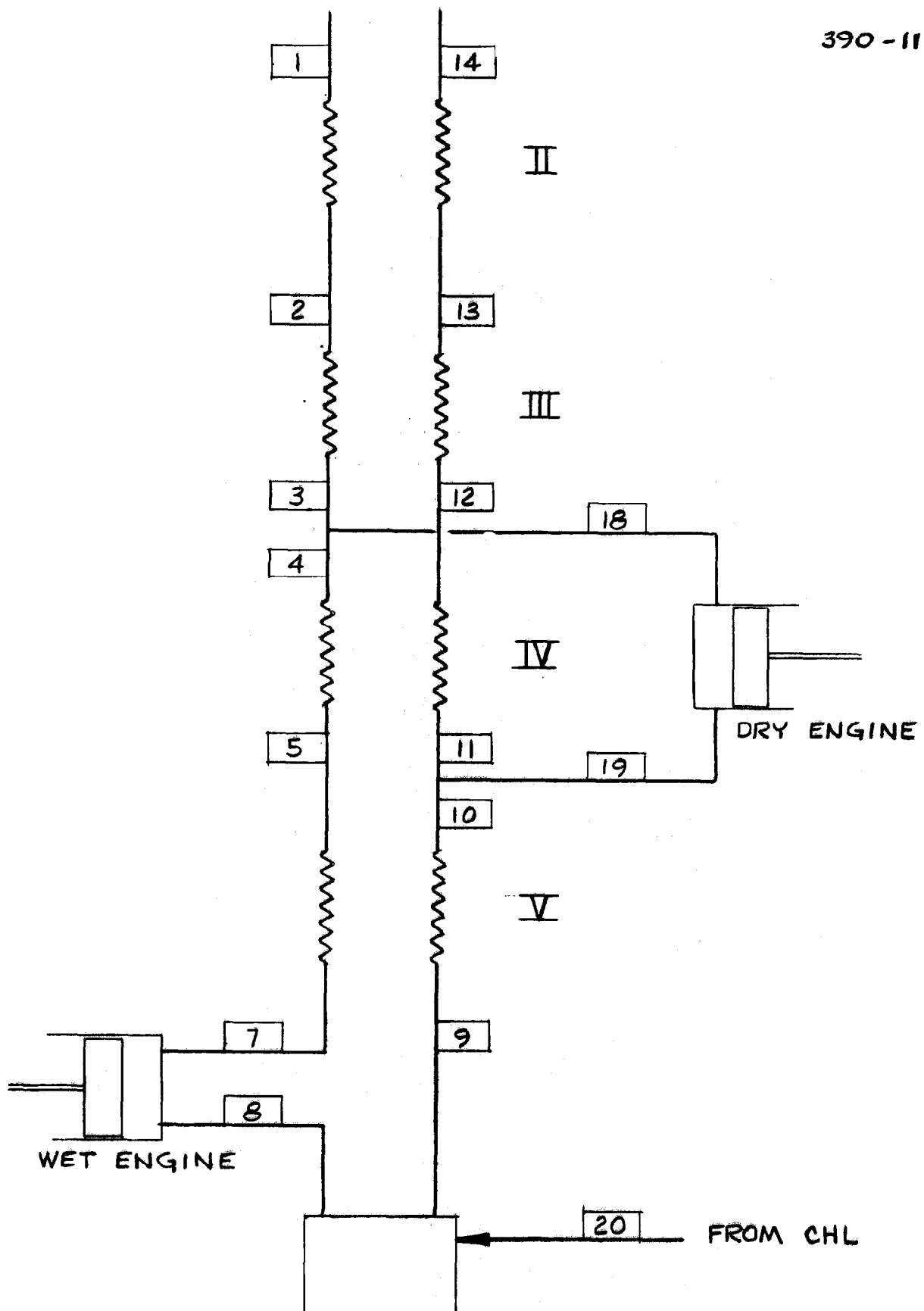
The effect of an enthalpy change of the liquid helium supplied from the CHL is not large. For instance, compare the liquid flowing in the distribution system at 4.5°K, but at two pressure levels of 2.0 and 10.0 ata. The enthalpies are 11.21 and 14.41 J/gr, respectively. The change is 3.2 J/gr, but only $.084 \times 3.2 = .27$ J/gr of flow circulated in the satellite refrigerator cold box. Therefore, system capability is not very sensitive to pressure level in the liquid helium distribution line.

To increase refrigeration capability of the system, one or more of the following may be considered:

- a) Increase satellite refrigerator circulating flow rate with a proportional increase in liquid helium supplied by the CHL. This method is at this time limited by available capacity of the CHL.
- b) Increase wet expander efficiency to obtain the maximum amount of refrigeration from the circulating flow rate of the satellite refrigerator.
- c) Increase satellite refrigerator flow rate beyond the maximum rate determined under a) above. Use the increased flow rate to generate refrigeration with the dry engine to make up for refrigeration normally supplied by an increased liquid helium supply.

IV. INCREASE IN SATELLITE REFRIGERATOR CIRCULATING FLOW RATE:

Figure 1 is the schematic flow sheet of the satellite refrigerator cold box, when operating in the satellite mode. Table III shows the process points of the flow schematic of Figure 1. The original satellite refrigerator was designed for a circulating flow rate of 37.9 g/sec. The low pressure circuit of the heat exchangers carries a flow rate of 41.1 g/sec. Pressure drop of the low pressure circuit was calculated to be .17 ata. This provides a lowest pressure in the two phase circuit of 1.2 ata, when the compressor suction is at 1.03 ata. A pressure of 1.3 ata for point 9 of Table III allows an increase of low pressure circuit flow rate by 26% to 51.8 g/sec.



FLOW SHEET SATELLITE REFRIGERATOR

FIG - 1

T A B L E I I I

<u>Point</u>	<u>Fluid</u>	<u>Pres.</u> <u>atm</u>	<u>Temp.</u> <u>°K</u>	<u>Enthalpy</u> <u>J/gr</u>	<u>Flow Rate</u> <u>g/sec</u>
1	He	20.8	300	1579.2	37.9
2	He	-	80	434.4	37.9
3	He	20.06	25.07	138.8	37.9
4	He	20.06	25.07	138.8	37.9
5	He	20.02	15.0	77.76	37.9
6	He	-	-	-	-
7	He	20.0	5.24	21.84	37.9
8	He	1.8	4.75	13.1	37.9
9	He	1.20	4.42	29.94	41.1
10	He	1.17	13.15	81.55	41.1
11	He	-	-	-	-
12	He	1.14	23.8	137.84	41.1
13	He	1.09	76.2	410.42	41.1
14	He	1.03	278.5	1466.1	41.1
20	He	1.6	4.6	11.91	3.2

The available refrigeration with the data of Table III is 696 W. Reference 1 (p. 78) indicates that the heat exchanger column of subsequent satellite refrigerators has been redesigned to provide a lower pressure drop. It, therefore, will be assumed that circulating flow rate of the satellite refrigerators has been increased to a point where the liquid helium supplied by the CHL is the controlling parameter. Reference 1 provides performance data for the satellite refrigerators as in Table IV:

T A B L E I V

Satellite Performance

Circulating Flow Rate:	53.1 g/sec
Liquid Helium Consumption:	129 ℓ /hr
Refrigeration Supplied:	966 W

V. INCREASE IN WET EXPANDER EFFICIENCY:

Wet expander performance required to realize the data of Table III is as shown in Table V:

T A B L E V

<u>Inlet Conditions</u>	<u>Discharge Conditions (Ideal)</u>	<u>Discharge Conditions (Actual)</u>
P = 20 ata	P = 1.8 ata	P = 1.8 ata
T = 5.24°K	T = 4.05°K	T = 4.75°K
H = 21.84 J/gr	H = 9.18 J/gr	H = 13.1 J/gr
S = 3.172 J/gr-°K	S = 3.172 J/gr-°K	
V _S = 6.36 cc/gr	V _S = 7.54 cc/gr	η = .69

Indicated efficiency is 69%. If we could achieve 100% efficiency, operating conditions could be as shown in Table VI:

T A B L E V I

<u>Inlet Conditions</u>	<u>Discharge Conditions</u>
P = 20 ata	P = 1.8 ata
T = 6.02°K	T = 4.5°K
H = 24.50 J/gr	H = 11.2 J/gr
S = 3.646 J/gr-°K	S = 3.646 J/gr-°K
V _S = 6.61 cc/gr	V _S = 8.11 cc/gr
	= 1.0

The inlet temperature of the expander has been raised. This reduces the UA of the heat exchangers in the cold box, and allows a slight decrease in the unbalance of the exchanger. The effect will be considered later. Additional refrigeration available from the satellite refrigerator has been increased by 100 W.

The consequences of a reduction in wet engine efficiency are important to note. If we assume Table VI to be the basis of the comparison, we find the available refrigeration from the satellite refrigerator at 1.2 atm to be as shown in Table VII (53.1 g/sec of circulating flow rate and 4.48 g/sec of liquid helium supplied).

T A B L E V I I

Wet Engine Efficiency %	Refrigeration Available W
100	1,126
90	1,056
80	985
70	915
60	844
50	773
40	702
20	561
0	420

Obviously, the wet engine is of extreme importance to the operation of the overall refrigeration system.

VI. INCREASE FLOW RATE TO SATELLITE REFRIGERATOR COLD BOX, KEEP LIQUID HELIUM SUPPLY FROM THE CHL CONSTANT, AND OPERATE DRY ENGINE:

Consider an increase in satellite refrigerator circulating flow rate to the wet engine of 20%, while maintaining CHL supplied liquid helium flow rate at 3.2 g/sec

(92 l/hr). Table III data will be used as the departure points. Also, wet expander efficiency as assumed in Table III will be used.

Table VIII shows the process points. It is necessary to verify that the heat exchangers of the satellite refrigerator cold box can meet the conditions of Table VIII. To compare heat exchangers for varying operating conditions, the parameter UA will be compared for the cases represented by Tables III and VIII data.

T A B L E V I I I

<u>Point</u>	<u>Pres. atm</u>	<u>Temp. °K</u>	<u>Enthalpy J/gr</u>	<u>Flow Rate g/sec</u>
1	20.8	300	1579.2	46.68
2	-	-	-	46.68
3	20.06	25.07	138.8	46.68
4	20.06	25.07	138.8	45.48
5	20.02	15.0	77.76	45.48
6	-	-	-	-
7	20.0	5.24	21.84	45.48
8	1.8	4.75	13.1	45.48
9	1.20	4.42	29.94	48.68
10	1.17	13.26	82.20	48.68
11	1.17	13.26	82.16	49.88
12	1.14	23.8	137.84	49.88
13	1.09	-	-	49.88
14	1.03	283.25	1485.84	49.88
18	20.06	25.07	138.8	1.2
19	1.4	13.15	81.55	1.2
20	1.6	4.6	11.91	3.2

Heat exchanger V cooling curve data are given in Table IX:

T A B L E I X						
HIGH PRESSURE			LOW PRESSURE			
T °K	H J/gr	ΔH J/gr	T	H	ΔH	1.070 ΔH
15	77.76	-0-	3.26	82.20	-0-	-0-
13	64.91	12.85	1.0	70.19	12.01	12.85
11	51.17	26.59	8.7	57.35	24.85	26.59
9	38.25	39.51	6.6	45.27	36.93	39.51
8	32.90	44.86	5.8	40.27	41.93	44.86
7	28.32	49.44	5.12	35.99	46.21	49.44
6	24.41	53.35	4.66	32.34	49.86	53.35
5.24	21.84	55.92	4.42	29.94	52.26	55.92

From Table IX data, we find:

$$\text{Heat transferred } Q = 8,723 \text{ Btu/hr}$$

$$\text{Log mean temperature difference } \Delta T_m = 4.18^\circ\text{F}$$

$$\text{Then } UA = \frac{Q}{\Delta T_m} = 2,086$$

Heat exchanger IV cooling curve is a function of the flow through the dry engine. To keep the UA of the exchanger at nearly the same value, we will assume that the temperature of point 12 of Figure 1 is again 23.8°K. A heat exchanger balance then determines the flow rate through the dry engine.

Heat transferred from high pressure stream between points 4 and 5 is $45.48 \times 61.04 \times 3.43 = 9,522 \text{ Btu/hr.}$

Stream 10 takes up:

$$48.68 \times 55.64 \times 3.43 = 9,290 \text{ Btu/hr.}$$

Stream 19 then needs to take up 232 Btu/hr. The enthalpy difference between streams 19 and 12 is 56.29 J/gr. Dry expander flow will be: 1.20 g/sec. With this expander flow, heat exchangers II and III will have a smaller ΔT_m when compared with the original case.

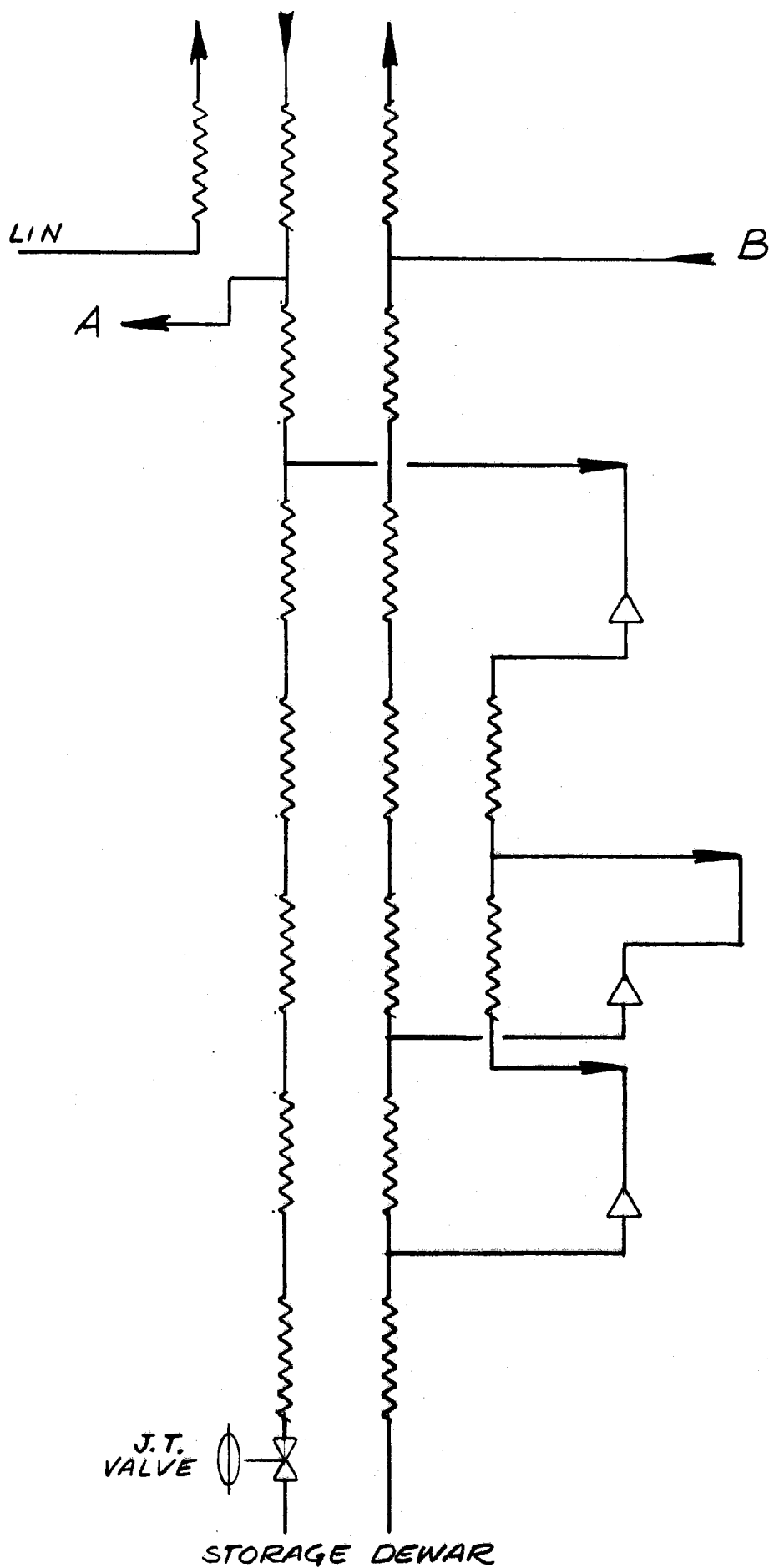
We find $UA = 21,350$ and $= 14,550$ for numbers of Tables III and VIII, respectively. It should be noted that the large difference in UA is partially the result of increased flow rate. Since heat transfer coefficients in first order are proportional to flow rate, relative difference, when ignoring change in flow, is approximately 20%. A lowering of the temperature of point 12 to 23°K will provide again the same UA for exchangers II and III. The change can be accomplished by increasing dry expander flow rate by 5.29 g/sec. Table X compares the available refrigeration from an increase of flow rate without change of liquid supply:

T A B L E X

	Flow Rate		Change %
	g/sec	g/sec	
Wet Engine:	37.9	45.48	20.0
Dry Engine, Max.:	-0-	5.23	-
Compressor Suction:	41.1	53.91	31.2
Liquid Helium From CHL:	3.2	3.2	-0-
Refrigeration Provided, W:	696.0	824.0	18.4

VII. INCREASE OF CHL CAPACITY:

Figure 2 is the schematic flow sheet of the CHL.² It will be noted that the refrigerator is equipped with a J-T valve. In principle, it is possible to use a wet expansion engine in lieu of the J-T valve. This engine could operate with inlet and discharge conditions as shown in Table XI:



STORAGE DEWAR

FIG-2

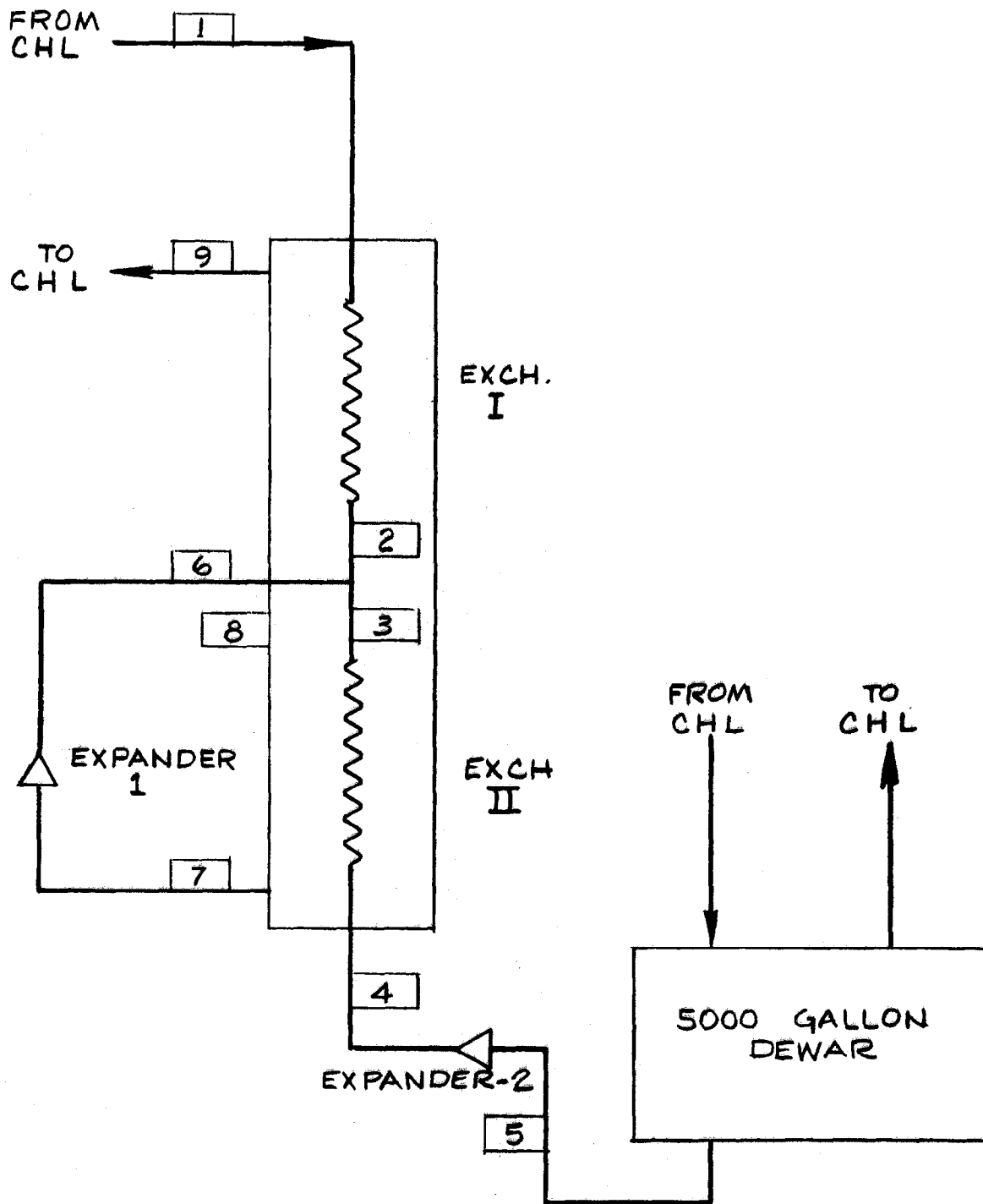
T A B L E X I

<u>In</u>		<u>Out</u>	
P =	11.0	P =	2.0 ata
T =	6.14°K	T =	4.85
H =	21.40 J/gr	H =	14.01
S =	4.196	S =	4.196
V _s =	7.575	V _s =	9.207 cc/gr
ΔH =	7.39 J/gr	ΔH =	5.40

Refrigeration supplied by the engine is then 1,681 W. This refrigeration will show up in the form of additional liquid supplied to the storage dewar. However, this extra liquid is not available for distribution to the magnet system, since the duty on the expanders of the CHL in that case would be much beyond their capability. In order to preserve the balance of the exchangers and turbines of the CHL, the refrigeration needs to be used in the storage dewar to keep the return flow of cold gas to the CHL at the same value.

Figure 3 shows a system which permits the use of the extra refrigeration to make additional liquid helium. Process points for this system are shown in Table XII. Stream 1 represents a small part of the high pressure stream of the CHL cold box (6.25%). Stream 9 is returned to the CHL cold box and joins the low pressure stream flowing to the compressor suction (5.65%) at point B.

The increase in flow rate in the warm exchanger of the CHL box is obtained by supercharging the compressor suction by 5.65% or .85 psig. Refrigeration provided by expanders 1 and 2 is 5,544 and 707 W, respectively. Stream 5 enters the storage tank as superheated vapor. However, reducing its enthalpy to that of liquid will consume the 1,680 W produced by the wet engine of the CHL. Therefore, the amount of additional liquid available is 17 g/sec or 490 lb/hr.

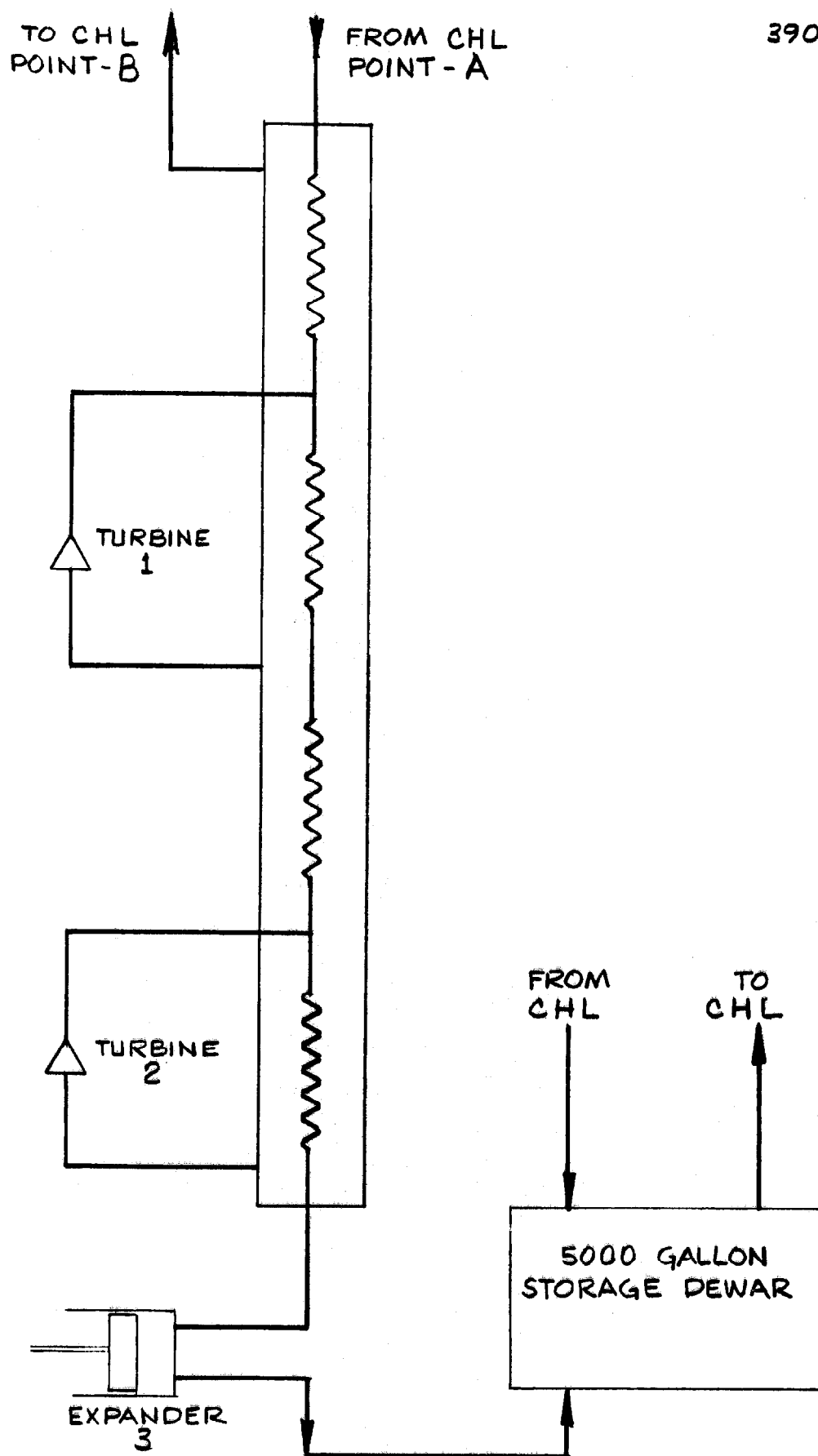
FIG - 3

T A B L E X I I

Point	Pres. atm	Temp. °K	Enthalpy J/gr	Flow Rate g/sec
1	11.2	81	437.7	83.4
2	11.2	42	232.7	83.4
3	11.2	42	232.7	17.0
4	11.2	27	151.8	17.0
5	3.0	18.8	110.2	17.0
6	11.2	42	232.7	66.4
7	1.4	26	149.2	66.4
8	-	-	-	-
9	1.4	80	430.4	66.4

It is possible to increase the production rate of additional liquid by increasing the flow rate to expander 1 of Figure 3 or by supplying a second turbine in parallel with expander 1, but operating at a lower temperature level. Stream 4 of Figure 3 then would be cooled to a lower temperature. Figure 4 shows the schematic flow sheet. It implies that the compressors of the CHL still supply the gas for operation of the secondary box. However, flow rates are rather large, and the CHL compressors may have to be supercharged to a level where the capacity of the CHL itself will decrease. It may then be necessary to provide additional compressor capacity to supply gas to the auxiliary liquefier. It now has become a complete liquefier.

The machinery required to provide the capability of producing an extra 490 l/hr of liquid helium consists of one turbine with gas bearings (expander 1) and two reciprocating engines for expander 2 and the wet engine of the CHL. Tables XI, XIII, and XIV provide the operating data for these machines.

FIG - 4

T A B L E X I I I

<u>Inlet</u>	<u>Discharge (Ideal)</u>	<u>Discharge (Actual)</u>
P = 11 ata	P = 1.4	P = 1.4
T = 42°K	T = 18.4	T = 26
H = 232.7 J/gr	H = 109	H = 149.2
S = 16.16 J/gr°K	S = 16.16	
ΔH = 123.7 J/gr		ΔH = 83.5

T A B L E X I V

<u>Inlet</u>	<u>Discharge (Ideal)</u>	<u>Discharge (Actual)</u>
P = 11 ata	P = 3.0	P = 3.0
T = 27°K	T = 16.0	T = 18.8
H = 151.8 J/gr	H = 95.76	H = 110.23
S = 13.77 J/gr°K	S = 13.77	
ΔH = 55.6 J/gr		ΔH = 41.57

REFERENCES

- (1) A Report on the Design of the Fermilab Superconducting Accelerator, May, 1979. Fermilab, Batavia, Illinois, p. 63.
- (2) Accelerator Division, Energy Doubler Project Specification No. 1660-ES-54605, Dec. 23, 1975; Technical Proposal C11501 by CTI, Inc., Waltham, Mass.